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ABSTRACT

Solar subsystems and components were identified and conceptual structure was developed for architectural solar energy heating and cooling systems. Recent literature related to solar energy systems was reviewed and analyzed. Solar heating and cooling system, subsystem, and component data were compared for agreement and completeness. Significant aspects of the analysis were the greatest consensus of systems, on-the-shelf availability, and cost-effectiveness of the solar systems. Six subsystems common to all solar systems were identified: collector, storage, distribution, transport, auxiliary, and control subsystems. Three components were found that could be common to all the solar heating and cooling systems--preheat domestic hot water, heat exchanger, and heat pump. Conceptual structures were developed for active and passive air and liquid solar heating and cooling systems. Hybrid solar systems, solar retrofit, and solar domestic hot-water systems were also studied. (The study is recommended as the basis for solar curriculum development.) (YLB)

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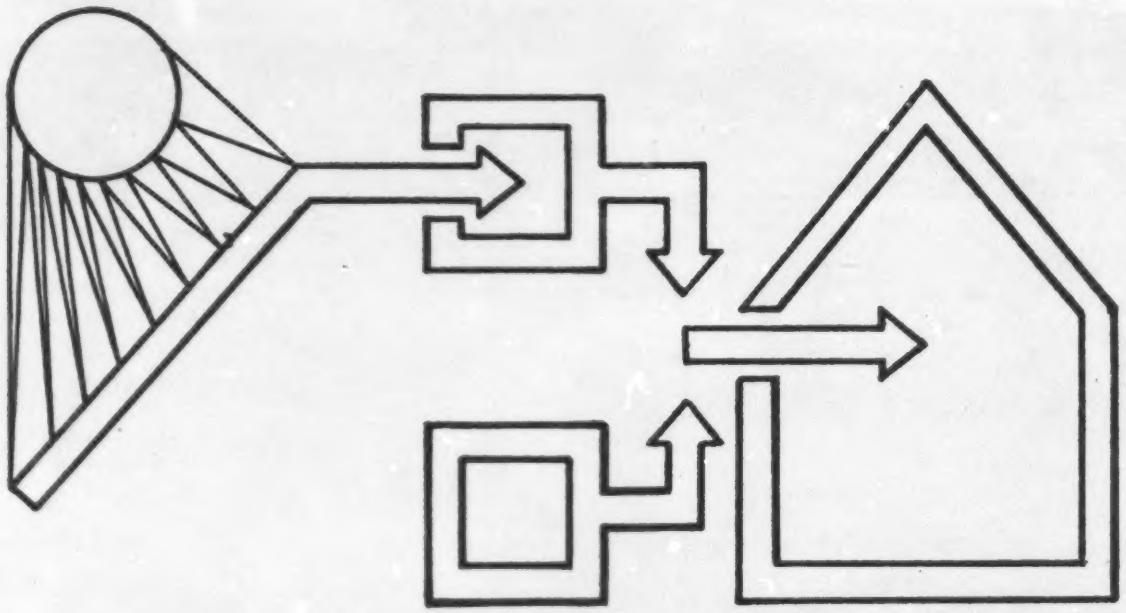
DEVELOPMENT OF A CONCEPTUAL STRUCTURE



FOR ARCHITECTURAL SOLAR ENERGY SYSTEMS

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May, 1979

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CHAPTER I

INTRODUCTION, STATEMENT OF THE PROBLEM, AND DEFINITION OF TERMS

Since man's beginning, nature has dictated the type of architecture that takes advantage of the sun's warmth. The early 1900's heralded an age of cheap and readily available sources of fossil fuels. This allowed the comfort of our environmental envelope to be controlled by mechanical systems rather than by natural means. However, the days of cheap and limitless fuel have been abruptly interrupted by the oil embargo in 1973, and the increasingly high cost of oil and natural gas. This has created a need for a reassessment of our long term energy supply resources.

The United States Energy Research and Development Administration (ERDA) was formed to analyze this need. ERDA Report No. 49, "National Solar Energy Research Development and Demonstration Program", indicates that a large portion of our total energy needs must be met by solar energy. ERDA's report projected that "The nation's total energy supply grows from today's 73 quads to 180 quads by the year 2020 A.D., and solar energy would meet 25% of this total, i.e. 45 quads" (Reuyl, Harman, Carlson, Levine, and Witwer, 1977, p. v).

Shortly after the assessments were made by ERDA, Congress passed the National Energy Act. The catalyic effect of this Act has thrust solar energy to the forefront of consideration as a viable alternative energy resource. This increased credibility plus the promised passage of both

the Photovoltaic Demonstration Act of 1978 and the Solar Energy Development Bank Bill will increase the consumer's desire to invest in solar heating and cooling systems.

Statement of the Problem

Solar energy as an emerging alternative energy source has created a need for an understanding of the basic systems contained in this new energy source. The problem is to identify the subsystems and components and to develop a conceptual structure for architectural solar energy heating and cooling systems.

Limitations of the Study

This study will be limited to the analysis of those solar heating and cooling systems that are technically feasible and commercially available today. These solar systems are: active heating, cooling, and domestic hot water systems; and passive heating and cooling systems. They offer the greatest potential to assist the national energy need for the next 20 years. Solar technology such as windpower, ocean thermal gradients, photovoltaic cells, bioconversion, ocean currents, hydropower, and central solar electric generators will not be considered in this study.

The use of solar heating and cooling systems received its greatest impetus from the oil shortage of 1973, therefore, this study is primarily concerned with those developments that occurred since that time. The review of literature, found in Chapter II, is made from sources developed after 1973 in order to utilize the most technical current data available.

The sources were limited to a review of related literature and studies concerned with the conceptual development of architectural solar heating

and cooling systems. This limitation enabled the study to focus on a larger national segment of the solar systems.

Definition of Terms

The terms used in this study that require clarification for complete understanding are:

Active System -	Is one that utilizes an energy resource, in addition to solar, to transfer thermal energy by pumps and blowers.
Componeat -	Is a single part that is recognizable in itself and forms a portion of a larger whole, i.e., a subsystem.
Passive System -	Is a system that utilizes solar energy alone, in addition to the natural phenomena of convection, radiation, and conduction to transfer thermal energy.
Quad -	Is a unit of measurement that equals one quadrillian (10 x 15) British Thermal Units (BTU).
Subsystem -	Is a small but complete portion of a larger system that performs some special function such as collector, storage, distribution, transport, auxiliary, or control.
System -	Is a grouping of subsystems and components to form a complete functional assembly for a particular purpose, i.e., solar heating and cooling of a structure.

Sources of Data

The sources of information used for the study were obtained from a thorough library search of literature related to solar energy. The criteria of relatedness and content validity were considered as important requirements for the basis of this study. Selected materials used during the study include such solar leaders and organizations as author Bruce Anderson; The American Society of Heating, Refrigerating and Air Condi-

tioning Engineers (ASHRAE); the United States Department of Housing and Urban Development (HUD); and the United States Energy Research and Development Administration (ERDA), now called The United States Department of Energy (DOE).

Importance of the Study

The limited supply of natural gas and oil necessitates a thorough review of all energy sources. The renewable and nonpollutant qualities of architectural solar heating and cooling makes it an attractive alternative energy source. The needed solar technology is available but its use has been limited because of misunderstanding, lack of trained personnel, and existing relatively high initial costs. The cost factor is expected to resolve itself through mass production techniques and the high inflationary rate of natural gas, oil, and electricity prices. However, education is necessary to bridge the solar energy credibility gap and to prepare trained personnel to meet the challenge of this new industry.

At the 1974 Solar Heating and Cooling of Buildings Workshop it was stated that the "Projected total potential market for cost effective solar energy installations is 40 million buildings by 2000 A.D..... a 15 billion dollar per year business" (Cohen, 1975, p. 6).

This study addresses the conceptual structure of those systems required for an understanding of solar heating and cooling. It will provide the technical foundation for the preparation of occupational/job task analyses, program goals and objectives, learning activities, and equipment and facility planning.

Method of Study

The method of study was accomplished through a review of recent literature related to solar energy systems. The sources of data were located from an educational search of books, documents and periodicals. Initially, The Education Index, Resources in Education, the Current Index to Journals in Education, Educational Resources Information Center, Book Review Digest, Encyclopedia of Educational Research, and Central Michigan University library book catalog index were reviewed for solar energy topics. This was followed by an analysis of related literature ranked according to its relevance to the problem statement. The resulting information was assimilated and grouped under the headings of solar heating and cooling systems, subsystems, and components. These groupings were made in outline form based on a priority order of importance to simplify the organization of solar data. It also enabled the analysis to develop from the general concept of solar energy systems to the specific subsystems and components. From this conceptual structure, major solar systems were identified as commercially available for today's energy market. These systems should assist the efforts of curriculum developers to formulate the educational curricula necessary to teach the role and function of solar architectural energy systems.

CHAPTER II

REVIEW OF RELATED LITERATURE

The energy crisis initiated a need for additional fuel sources. The role of solar heating and cooling, as an alternative energy, has received a great deal of attention. Relevant information for the development of the conceptual structure of solar systems, subsystems, and components were made and/or sponsored by the Federal Government, professional organizations, and other leaders in the solar industry.

One of the most outstanding leaders is Bruce Anderson, executive editor of Solar Age Magazine. Anderson (1976) indicates that "the variety of solar systems are grouped into three broad categories -- direct, integrated, and indirect" (p. 14).

Active Air and Liquid Solar Heating and Cooling Systems

The indirect or active solar heating and cooling systems are most often thought of when we talk about solar energy. They are the solar systems that are the most promising for the next 20 years because of their adaptability to existing structures. This adaptation is called retrofitting.

Solar systems are divided into two heat collecting and transporting mediums - liquid or air. "When personal comfort requires only space heating, air-type transport systems are favored because of their relative simplicity and long lifetimes.... If cooling is needed in addition to heating, a liquid system is a more likely choice than an air system"

(Anderson, 1976, pp. 149-150). If domestic hot water is included in the solar heating and/or cooling system, a liquid heat transport is used.

> Indirect systems for solar heating generally use rooftop solar collectors and separate heat storage devices. Heat moves from the collectors to storage or to the rooms by indirect routes..... Pumps or fans are required to circulate liquids or air through the collector and back to the insulated heat storage container, often a tank of water or a pile of rocks. When the house needs heat, air or water from the house heating system is warmed by the stored heat and circulated to the rooms. Indirect heating systems ... are also called active systems .... are very popular because they require little owner attention, are more readily applied to existing homes, and are more intriguing to a gadget-loving society (Anderson, 1976, pp. 14-15).

The Solar Dwelling Design Concepts developed by the American Institute of Architects (AIA) Research Corporation for the U.S. Department of Housing and Urban Development presents a general development of solar heating and cooling concepts and is cited as (HUD, 1976) throughout this research. The development of the conceptual structure for solar heating and cooling systems "consists of three generic components: collector, storage and distribution and may include three additional components: transport, auxiliary energy system and controls" (HUD, 1976, p. 17).

Collector Subsystem

With either a liquid or an air medium, the most important subsystem, the collector, can be selected. The collector subsystem captures the sun's

rays and converts them to thermal or electrical energy. Photovoltaic collectors are utilized to convert solar radiation into electrical energy. Thermal collectors convert solar radiation into heat energy.

The Intermediate Minimum Property Standards Supplement For Solar Heating and Domestic Hot Water Systems, cited here after as (MPS, 1977), indicates that the collector consists of three different kinds: the flat-plate collector, the evacuated tube collector, and the concentrating collector. The most common is the flat-plate collector. It also consists of three types: the fluid tube and plate collector, the trickle water collector, and the flat-plate air collector. The flat-plate collectors are mainly used for low temperature residential solar heating and domestic hot water systems (MPS, 1977).

Flat-plate collectors can also be used with a forced-air heating or cooling distribution subsystem. The air collector is blown directly into the space whereas a liquid collector transfers heat through a coil. The advantage of this distribution subsystem is that it allows the application of a solar retrofit to an existing conventional forced-air system.

High temperature solar applications require the evacuated tube or the concentrating collector. The evacuated tube collector absorbs solar radiation in a vacuum tube containing metal or glass fins that transmit the absorbed solar energy to a gas or a liquid transporting medium (MPS, 1977).

The concentrating collector focuses solar radiation to a single axis and is comprised of a reflector, an absorber, a housing, and a tracking device. Several different kinds of concentrating collectors are available. They include ... "linear and circular concentrators, lens focusing collectors, collectors with directional and non-directional focussing and tube concentrators" (MPS, 1977, p. C-22).

Solar cooling systems utilize a liquid solar collector, storage, and distribution subsystem. Absorption cooling equipment requires high temperatures that cannot be delivered by either an air system or a flat-plate collector. Therefore, a liquid system with a concentrating or an evacuated tube collector are necessary.

Storage Subsystem

The storage of the excess collected heat is the second major system of solar heating and cooling systems. The storage subsystem holds the excess collected heat when it is needed at night or on cloudy days. Storage can be achieved by any one of two methods, sensible or latent heat storage. Sensible heat storage consists of room air, concrete mass, rocks, pebble bins, or water tanks. Latent heat storage consists of phase change chemicals such as eutectic salts or paraffin (HUD, 1976).

The type of storage depends upon the solar system, either air or liquid, that is being used. "Until phase-changing salts are cheap and reliable, the main choices for heat storage are (1) large tanks of water and (2) rock or gravel beds. Water tanks occupy from one-third to one-half the volume that rock beds need for the same amount of heat storage" (Anderson, 1976, p. 151).

A liquid collector subsystem uses the sensible heat storage of water for maximum cost effectiveness "a capacity of 50 kilograms of water per square meter of collector area results in maximum system efficiency" (Cohen, 1975, p. 8). This equals approximately 110 pounds of water per 1.1 square yard of collector area.

Heat Exchanger Component

In liquid solar heating and cooling storage subsystems, a heat exchanger component is used to transfer thermal energy from one fluid to another. It separates the collector fluid from the domestic potable water supply. There are three common types in use today: shell and tube, shell and double tube, and double wall. The shell and tube heat exchanger is used to transfer heat from one nontoxic medium to another. The shell and double tube and the double wall heat exchangers are used whenever toxic fluids are contained in the collector system (MPS, 1977).

Heat Distribution Subsystem

A third major subsystem of solar heating and cooling systems is the heat distribution. This subsystem takes the collected or stored energy and transports it to the demand area. The transport medium can be either radiation, air, or liquid carried by the components convection, ducts, or pipes respectively. "An indirect system usually needs more heat exchangers, piping, ducts, pumps, fans, and blowers to get the heat inside the house" (Anderson, 1976, p. 194).

The distribution subsystem of the combined solar heating and domestic hot water system consists of six typical kinds: a warm air distribution with a hot water coil in the duct, hydronic distribution, individual fan coil unit distribution, radiant heat distribution, warm air distribution from rock storage, and a heat pump distribution (MPS, 1977).

Transport Subsystem

The fourth major subsystem, the transport subsystem, moves the thermal energy from the collector to the storage. Passive solar heating and cooling systems incorporate the natural phenomena of convection, conduction, radia-

tion, and thermosyphoning to perform the transport function. In active solar heating and cooling air and liquid systems "this component consists of pumps, valves, and pipes, or blowers, dampers and ducts" (HUD, 1976, p. 19).

Auxiliary Subsystem

A fifth major subsystem of solar heating and cooling systems is the auxiliary or back up system. Most solar heating and cooling systems are designed to provide 50 to 60 percent of the heating or cooling load. Therefore, an auxiliary system is required to provide for the additional heating and cooling requirements. Even in those areas where a 100 percent solar energy is designed, building codes require a back up system. It

> ... may operate independent of or in conjunction with the solar system. This is usually accomplished by locating the auxiliary energy system between the storage and distribution components to permit a full or partial operation, or by supplying the energy directly to the heat storage component thereby raising it to a usable temperature (HUD, 1976, p. 19).

Heat Pump Component

The increased use of the heat pump is being accepted by building authorities as a back up for solar systems. The heat pump permits a greater utilization of solar energy particularly when solar heating and cooling systems are combined. It absorbs heat from temperatures as low as 40°F (4.5°C) and extends the storage capacity of a solar heating and cooling system.

The solar-assisted heat pump component operates from the thermal solar storage tank when storage temperatures are too low to provide direct

heat to the structure. If the outside air temperature is above 23°F (-5.0°C) and the solar storage temperature is "below 90°F (32.2°C) and above 23°F (-5.0°C), the heat pump operates in its normal heating cycle" (Jardine, 1975, p. 146). If the outside air and solar storage temperatures fall below 23°F (-5.0°C), an auxiliary heating component operates to heat the building directly or to raise the solar storage temperature. The heat pump efficiency drops off significantly below a temperature of 40°F (4.5°C). During the summer, the heat pump reverses its cycle and operates on a normal cooling mode (Jardine, 1975).

The heat pump can also be modified to use solar energy for cooling by incorporating a solar-powered heat engine to generate mechanical torque to drive the heat-pump compressor. For this study we used a Rankine cycle with Freon as the working fluid. Solar energy supplies heat input to the boiler of the Rankine engine. The Rankine engine can be decoupled from the system when solar energy is unavailable and the compressor can be driven by an electric motor (Cohen, 1975, p. 7).

Control Subsystem

To provide the needed heating or cooling, controls are required throughout the solar system. They are the sixth major subsystem of a solar heating and cooling system, since control is vital to the performance of all systems.

The control subsystem detects the heat or cooling needs of the space and responds by the delivery of the conditioned air from the collector, storage, or auxiliary subsystem. They can be either automatic or manually controlled. The control mechanisms form the basis for the two general

types of solar systems, active or passive. Passive solar systems utilize "solar energy alone for the transfer of thermal energy" (MPS, 1977, p. C-2). Active solar systems utilize additional energy to operate pumps and blowers for the transfer of thermal energy.

Passive Air and Liquid Solar Heating and Cooling Systems

The direct or passive method of solar heating and cooling systems utilizes the design of the building structure to collect and store the sun's heat. South facing glass allows the entrance of solar radiation to penetrate and be absorbed by the building materials. This heat absorbent storage capacity of building materials is called specific heat. It forms the basis of direct solar heating in conjunction with the shape, site orientation, and insulation of the structure (Anderson, 1976).

The integrated method utilizes "ingenious adaptations of the natural thermal properties of materials to collect and distribute heat" (Anderson, 1976, p. 14). Both the direct and the integrated methods are passive solar systems because of their lack of reliance on mechanical devices. They depend on the natural phenomena of convection, conduction, radiation, and the principle of thermosyphoning.

Additional heat storage capacity is available through the use of a vertical wall collector made of concrete, facing south, and covered with a double layer of glass. The three solar subsystems: "solar collection, heat storage, and heat distribution are combined in one unit" (Anderson, 1976, p. 121). The concrete wall is called a Trombe Wall named after Professor Felix Trombe, a pioneer of thermosyphoning air collectors. The thermosyphoning principle involves the use of hot air or water rising and cold air or water falling to carry heating and cooling to a structure.

The rising of hot air is referred to as the chimney effect (Anderson, 1976).

Another form of the integrated system is the use of a water wall collector of 55-gallon drums arranged vertically or horizontally. The advantage of a water wall versus a concrete wall is its superior thermal storage capacity.

A third form of the integrated system is the use of containers of water on a flat metal deck roof. "The solar heat collected in such roof ponds is radiated directly to the rooms below" (Anderson, 1976, p. 134). The roof pond system offers the benefit of reversing its cycle for cooling better than either the Trombe wall or the water wall.

A fourth form of the integrated solar system is the attachment of a south facing greenhouse. The greenhouse is nothing more than an extension of the glass front away from the Trombe wall. This extension provides a greater thermal storage volume of the collected solar energy. The greenhouse offers an additional advantage of extending the growing season, purifying the air, and is easily added to an existing house.

A warm air passive solar heating system usually consists of a "massive south facing wall of either concrete or masonry separated by an air space from an outer wall of glass, captures direct, diffuse and reflected solar radiation" (HUD, 1976, p. 37). The massive wall also serves as the storage subsystem and distributes heat to the dwelling by radiation, convection, and conduction. The control is maintained by manually operated dampers. Any conventional heating system can be employed as the auxiliary back up. One notable disadvantage of this solar system is its inability to combine domestic hot water with the masonry wall collector.

Solar Heating and Cooling Systems

The active and passive solar heating and cooling systems function in four distinct modes. The first function utilizes the converted solar energy directly to heat the structure. The second operation places the converted solar energy in storage when the structure does not require heat. The third operation distributes the solar energy from the storage to heat the structure when the sun is not shining. The fourth operation utilizes an auxiliary heating system when the stored solar energy is depleted and no additional sun is available. The four modes described are the collector, the storage, the distribution, and the auxiliary subsystems respectively. These four subsystems in addition to the transport and control subsystems form the basis for the development of four common solar heating and cooling systems. These four solar systems are: a warm water flat-plate active system, a warm air flat-plate active system, a warm water concentrating active system, and a warm air passive system previously described (HUD, 1976).

The warm water flat-plate solar heating active systems "consist of a collector; storage; a system of piping, and controls for circulating water from storage through the collector; and a distribution network for transferring stored heat to the dwelling" (HUD, 1976, p. 32). The water contains a noncorrosive antifreeze mixture and is separated by a double wall heat exchanger. Water lines are coiled in the storage subsystem prior to entry into the domestic hot water tank. This method makes up the hot water preheat component. The back up auxiliary is provided by a gas-fired conventional boiler (HUD, 1976).

The warm air flat-plate solar heating active systems "differ from warm-water systems in that air is used to transfer heat from collector

to storage..... Heat stored in the rock pile can easily be distributed... by a forced air system" (HUD, 1976, p. 34). The auxiliary energy subsystem is a conventional forced-air system used with a heat pump, an absorption unit, or a Rankine engine. The domestic water can be preheated by running the water line through the rock storage prior to entry into the hot water tank (HUD, 1976).

The warm water concentrating active system provides the high temperature water necessary for a solar cooling system. It consists of a concentrating evacuated tube collector, a water storage tank, a heat exchanger, and a pump to transport the solar hot water from the collector to the heat exchanger. Domestic hot water is preheated in the storage tank and the auxiliary subsystem is provided by either an oil or a gas-fired furnace. The advantage of this system is its availability for solar cooling as well as solar heating (HUD, 1976).

Cost Effective Solar Heating and Cooling Systems

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) is a leader in the energy industry. The members of this professional group are more affected by solar energy than any other current organization since it will become their responsibility to design and utilize solar heating and cooling systems.

In 1974, ASHRAE conducted a seminar in Washington, D.C. The results were published in the manual entitled Proceedings Of The Workshop On Solar Heating And Cooling Of Buildings, 1975. This publication consists of a series of solar energy presentations by well-known educators, professional engineers, and scientists. Its highly technical content relies on the solar state-of-the-art and provides a proof-of-concept analysis of the future solar heating and cooling role in the energy market.

The paper presented by Arnold Cohen, Program Manager, Space Division of General Electric Company compares the economics of a solar active system with a conventional electric heating and cooling system. Cohen (1975) analyzed the solar heating and cooling of eighteen different types of structures in twelve U.S. cities of varying climates. Twenty different solar heating and cooling system models were arranged and studied. The solar systems selected as cost effective and feasible by the proof-of-concept experimentation are the direct solar heat exchange, the solar-assisted heat pump, and the solar absorption cooling system. The solar Rankine cooling systems were also analyzed but "are not currently practical for cooling only operations... Cycle improvements and cost reductions could require a second look at this concept in future studies" (Cohen, 1975, p. 11).

The auxiliary back up subsystem is an electric resistive heating system. Since electric energy can be produced from various processes, it is anticipated that the future trend will be a decrease use of natural gas and oil with an increase use of electricity for the heating and cooling of buildings.

Cohen (1975) indicates that the direct solar heat exchange system is economical in all parts of the U.S. when compared with electrical heating and "in northern climates where cost of fossil fuel and heating loads are high" (Cohen, 1975, p. 17). The solar-assisted heat pump is also economical when compared with conventional electrical heating systems in northern climates, with fossil fuel heating in the southern climates, and wherever the annual cooling loads are approximately equal (Cohen, 1975).

The solar absorption cooling component utilizes the direct solar heat exchange system to perform its cooling function. The absorption cooling

equipment requires high temperatures and therefore an evacuated tube concentrating collector will be necessary.

The solar absorption cooling is uneconomical when used for cooling alone. It "is best used as an add on to a cost effective solar heating system in medium sized buildings where summer cooling load is high and winter heating demand is moderately high" (Cohen, 1976, p. 17).

At this same workshop, Albert Weinstein, manager of Special Energy Systems for Westinghouse Electric Corporation, analyzed solar heating and cooling systems for six building types. The structures were located in five different regions throughout the country. Ninety possible combinations of solar systems, subsystems, and components were arranged to supply 50 to 80 percent of the buildings heating and cooling load. The most feasible, economical, and available solar systems capable of these loads were selected. They consisted of three systems similar to Cohen's (1975) findings: the solar heating only, the solar-assisted heat pump, and the solar absorption heating and cooling system (Weinstein, 1975).

They were evaluated on the basis of a flat-plate collector subsystem using both air and water with a sensible heat storage subsystem of rocks and water respectively. The latent heat storage capability of eutectic salts offers the possibility of reducing the solar storage volume. However, the unstable nature of this salt after a period of repeated phase changes eliminates its use at this time.

The solar heating only system and the solar-assisted heat pump system function similar to the previously discussed systems whereby solar heat energy is directly transported to areas of demand or to the storage subsystem.

The solar cooling system was evaluated on the basis of six different cooling components: the absorption, the adsorption, the jet ejector, the

Rankine cycle inverse Brayton cycle, the Rankine cycle vapor compression, and the night radiation systems (Weinstein, 1975).

> Absorption systems using water as the refrigerant in a lithium bromide solution are the most immediately promising methods of utilizing solar energy for cooling. Other techniques, includ-ind Rankine cycle absorption systems or night sky radiation, have not been developed to the same stage of manufacturability (Weinstein, 1975, p. 41).

Weinstein (1975) compared the cost effectiveness of the three solar systems with conventional oil and gas heating in contrast to Cohen (1975) who compared solar cost effectiveness with electric heating and cooling. Weinstein (1975) indicates that direct solar heating systems will be cost effective for commercial and institutional buildings by 1980. Combined solar heating and cooling systems will be cost effective by 1985-90.

In conclusion, it is important: to identify the systems, subsystems, and components of the solar conceptual structure for a complete understanding; to relate the specific functions of the major solar subsystems to know the working relationship of each component; and to identify those solar systems that are reliable, feasible, economical, and available for today's market.

CHAPTER III

ANALYSIS OF DATA

The identification of the components and the development of the conceptual structure for architectural solar heating and cooling systems is accomplished through an analysis of the related literature. Solar system, subsystem, and component data are compared for agreement and completeness. The greatest consensus of systems, the on-the-shelf availability, and the cost effectiveness of the solar systems are significant aspects of this analysis.

Solar Subsystems

In order to establish a basic understanding of the solar heating and cooling systems, the six subsystems common to all solar systems are shown in Figure 1. This illustration is important because it orientates the reader through the use of readily recognizable shapes for the collector, storage, distribution, transport, auxiliary and control subsystems.

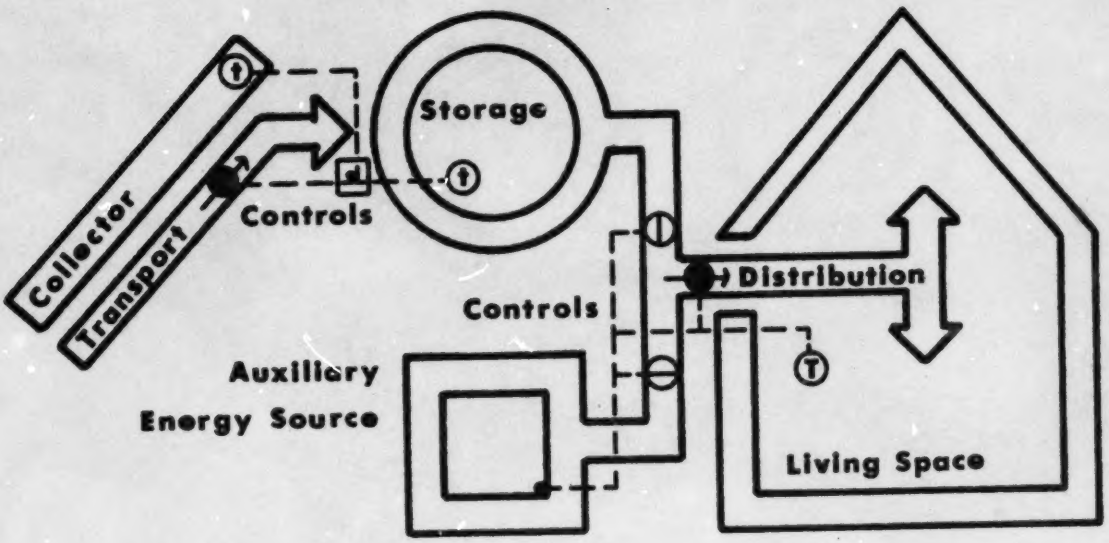

Figure 1.
A SOLAR SYSTEM

Redrawn from HUD, Solar Dwelling Design Concepts, p. 18

Figure 1 graphically displays the operation of a solar system and is defined as,

> The basic function of a solar system is the conversion of solar radiation into usuable energy. This is accomplished in general terms in the following manner. Radiation is absorbed by a collector, placed in storage, with or without the assistance of a transport medium, and distributed to point of use-an occupied space. The performance of each operation is maintained and monitored by automatic or manual controls. An auxiliary energy system is usually available for operation, both to supplement the output provided by the solar system and to provide for the total energy demand should the solar system become inoperable (HUD, 1977, p. 32).

Anderson (1976) and Cohen (1975) use five of the subsystems in the development of solar heating and cooling systems. HUD (1977) and MPS (1977) refer to a sixth subsystem, the transport subsystem.

Anderson (1976), MPS (1977), and HUD (1977) categorize solar heating and cooling systems as either active or passive depending upon the system's reliance on a mechanical energy source in addition to solar energy. The medium employed to collect solar energy for an active or passive solar system can be either air or liquid. These two fluids form the main classifications of solar heating and cooling systems. They consist of four distinct types: warm air passive, warm liquid passive, warm air active, and warm liquid active.

A third active solar system, called the photovoltaic system, converts solar energy directly into electrical energy. It is not pursued in the research because

> Photovoltaic systems are not currently competitive with thermal systems, although recent research suggests significant potential. To become economically attractive for application to buildings, the cost of cells must be reduced from the present commercial price of $20 per peak watt to $.20 per peak watt (Weinstein, 1975, pp. 41-42).

Solar Heating and Cooling Systems

The conceptual structure of the solar heating and cooling systems is graphically represented with the relationship of the six common sybsystems in Figure 2. In this figure are shown three components that can be common to all the solar heating and cooling systems. These three common components are the preheat domestic hot water, the heat exchanger, and the heat pump.

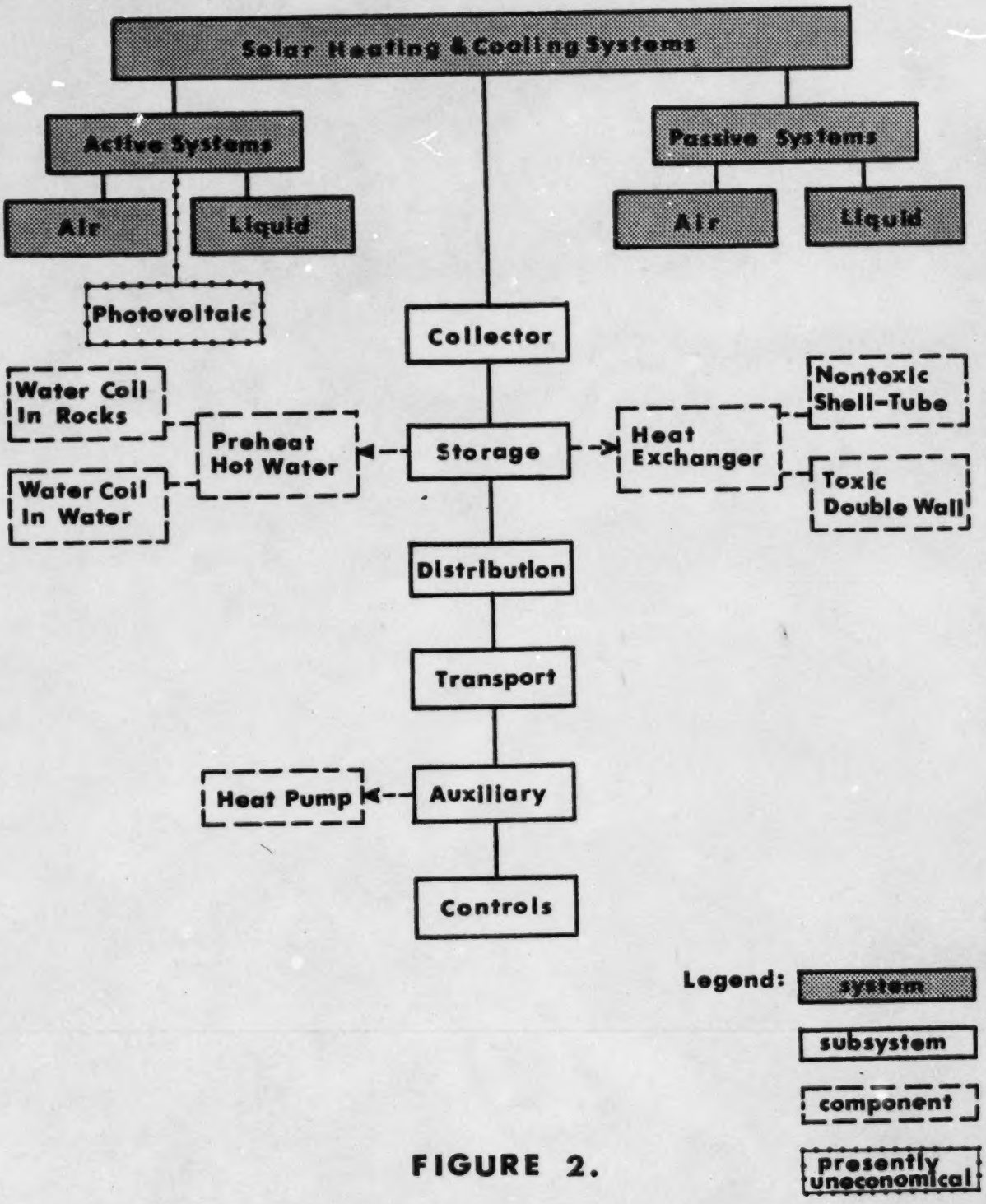

FIGURE 2.

A CONCEPTUAL STRUCTURE OF SOLAR HEATING AND COOLING SYSTEMS & SUBSYSTEMS

The preheat domestic hot water component is contained in the storage subsystem. The most common method is to simply coil the domestic water line through the liquid or rock storage prior to entry into the hot water tank.

The heat exchanger component is also contained in the storage subsystem. It exchanges the heat from the collector fluid to the storage fluid and prevents mixing with the potable water supply.

The heat pump component is contained in the auxiliary subsystem. "At this point, it is important to realize that a heat pump is not electric heat. Actually, it is a type of solar heating which draws heat from the surrounding air" (Dagostino, 1978, p. 393). Heat pumps can also draw heat from water. However, "the most commonly used surrounding mediums are the outside air and the forced air in the ductwork" (Dagostino, 1978, p. 392).

Active Air and Liquid Solar Heating and Cooling Systems

Figure 3 illustrates the conceptual structure for architectural active air and liquid solar heating and cooling systems. Solar air cooling active systems are in the experimental stage and are not shown in figure 3. The systems are identified by a solid line and shaded area.

The six common subsystems are identified by a solid line and organized in order of priority. The major subsystem of all solar heating and cooling systems is the collector. Anderson (1976), MPS (1977), HUD (1976), Cohen (1975), and Weinstein (1975) concur that the low temperature flat-plate collector is cost effective for both the air and liquid active solar heating systems. MPS (1977) describes two flat-plate collectors that are used with the liquid heating system. They are identified as the fluid tube and plate collector and the trickle water collectors.

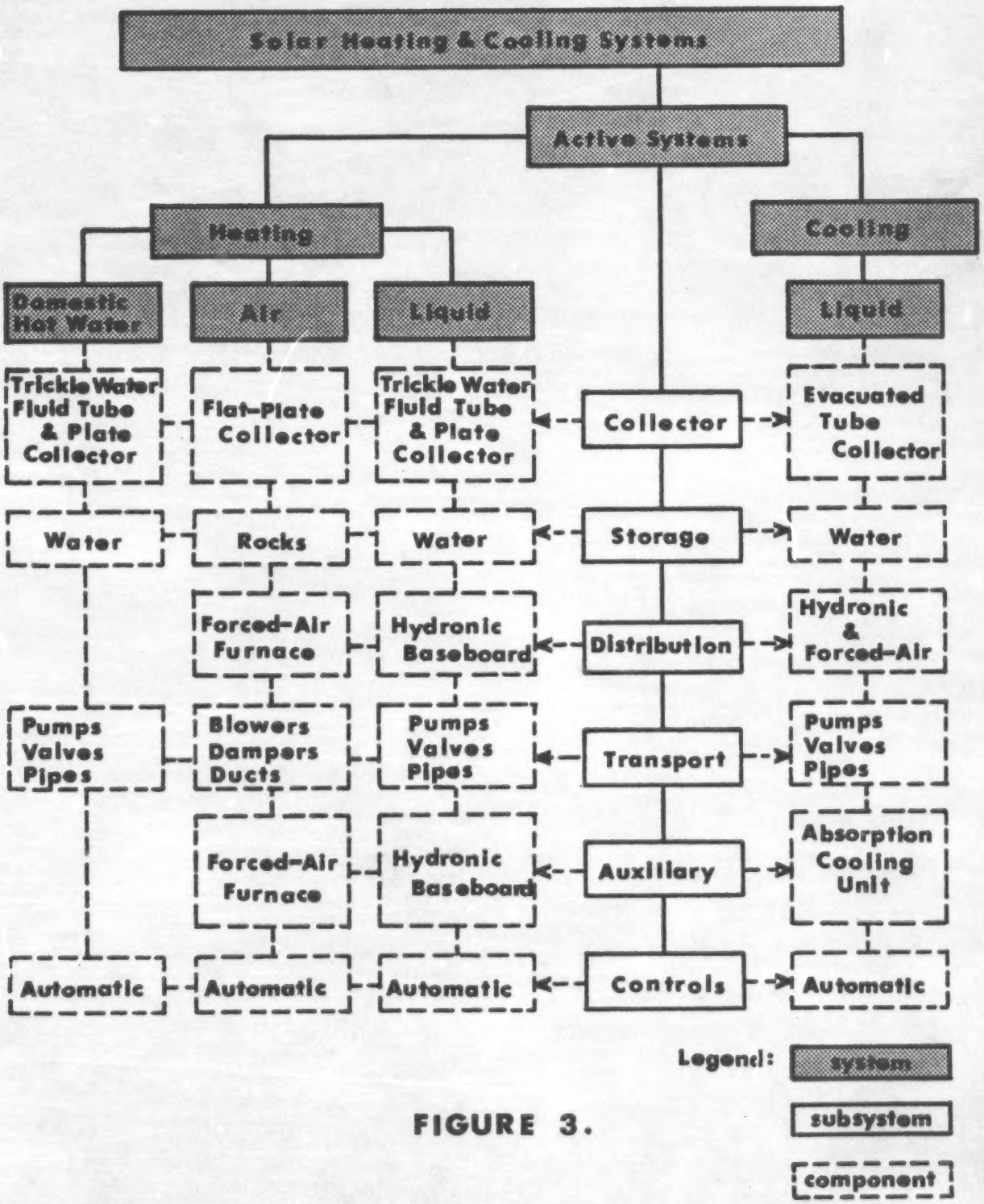

FIGURE 3.

A CONCEPTUAL STRUCTURE OF ACTIVE SOLAR HEATING AND COOLING SYSTEMS, SUBSYSTEMS, & COMPONENTS

The low temperature flat-plate collectors are efficient because they operate at temperatures compatible with conventional heating systems. Temperature loss is minimal because of the small difference between the outside and collector air temperatures. Usable heat is produced sooner than high temperature collectors. Low temperature collectors react faster to solar changes and collect diffused and reflected light. The high temperature collectors are necessary for the solar cooling active liquid systems. The evacuated tube collector is the most adaptable for this application (Anderson, 1976).

Storage is the second most important subsystem and is identified as a rock bin component for air systems and a water tank component for liquid systems. The collector-to-storage relationship is usually air-to-air and liquid-to-liquid respectively. The preheat domestic hot water is compatible with either the air or liquid storage.

Distribution subsystems transmit the heating or cooling to the space demand load. Warm or cool water is pumped from either the collector or storage through a piping coil that exchanges its temperature to the passing air of a forced-air component. The solar liquid piping coil carries the heated water directly into a conventional hydronic baseboard component.

The transport subsystem employs pipes and ducts to carry the heat medium from the collector to either the storage or distribution subsystems.

The auxiliary back up subsystem can consist of any conventional heating or cooling component. Like the storage subsystem, the auxiliary is compatible with the medium used to collect the solar energy. A forced-air furnace component is combined with a warm air active system. A hydronic baseboard component is combined with a warm water active system. The cost effective cooling back up component is the absorption cooling unit.

The control subsystem is comprised of automatic sensor and transducer components. They provide the comfort zone required and lend the solar system to an energy management capability.

Passive Air and Liquid Solar Heating and Cooling Systems

Figure 4 presents the conceptual structure of passive solar heating and cooling systems, subsystems, and components. The passive solar systems contain the six major subsystems similar to active. However, passive systems are integrated into the structure such that the basic architectural components of glass, roof, floor, space, and walls perform the subsystems' functions. The passive system does offer the advantage of solar cooling with air; whereas active solar air cooling systems are not feasible.

The collector and storage subsystems use either air or water depending on whether the solar system is air or liquid. As previously indicated for active solar systems, passive systems also operate on an air-to-air or liquid-to-liquid collector-to-storage relationship.

It is obvious from the conceptual structure that there is a large degree of commonality between the components of each type of passive solar system. This allows the solar passive system to be simple, versatile, economical and compatible with man's environment. The components -- the concrete wall, the greenhouse, the water wall, the roof pond, the room air, and the architectural construction perform the operation of two and even three subsystems. For example, the concrete wall component functions as the collector, storage, and distribution subsystem.

A flat-plate collector can be used with the solar passive liquid heating system. This collector is identical to the active subsystem previously described. However, the passive system uses the principle of

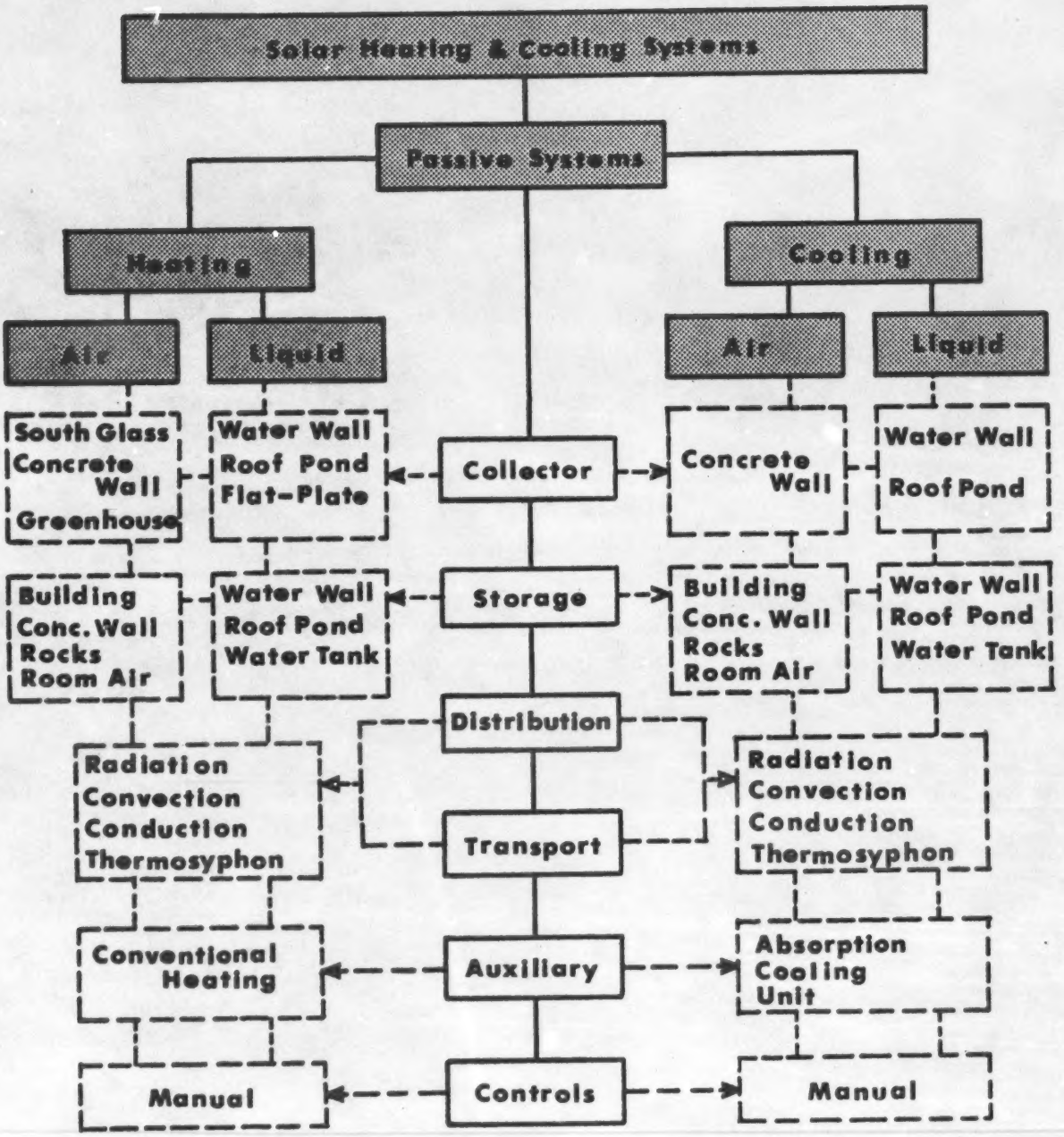

FIGURE 4.

A CONCEPTUAL STRUCTURE OF PASSIVE SOLAR HEATING AND COOLING SYSTEMS, SUBSYSTEMS, & COMPONENTS

thermosyphoning in lieu of pumps to transport the liquid across the face of the collector to the storage or to the point of distribution. This principle of warm fluids rising and cool fluids falling, plus the natural phenomena of radiation, convection, and conduction perform the distribution subsystem function. Because these components are intrinsic to the passive architectural structure they also perform the operation of the transport subsystem. The dual performance of components to operate the various modes of the subsystems greatly enhances the success and economics of solar passive heating and cooling systems.

The auxiliary back up subsystem is similar to that required for the active and can be any conventional type heating and absorption cooling unit. The control subsystem consists of manually operated devices such as dampers, ventilating sash, and insulation panels.

The inherent advantage of the passive solar heating and cooling system is also its disadvantage. The heat and cool absorbing capacity of architectural building components have a slow inertia turnover of temperature due to their mass. The reaction time to temperature change is slower than an active solar system and should be recognized and dealt with for the complete comfort of the occupants (HUD, 1976).

Hybrid Solar Systems

This disadvantage of passive systems and the disadvantage of the high collector cost for an active solar system can be offset by combining the best aspects of both solar systems. The combination is a hybrid solar system and offers the advantage of flexibility, cost effectiveness, better control, less reliance on the auxiliary subsystem, and greater comfort. This is accomplished by a comparison of the various components' compati-

bility. The components can then be matched and organized into a hybrid solar system designed for heating and cooling.

Solar Retrofit

The ability of a system to be added to an existing structure is retrofit. The mechanical nature of active solar systems allows the subsystems to be indirect or removed from each other. The ability of the collector to be resonably remote from the storage and/or distribution subsystems enables the active solar system to be applicable to existing buildings. This is the reason Cohen (1975) and Weinstein (1975) confined their study of cost effective solar systems to three types of active systems.

The passive solar air heating system has a retrofit capability through the addition of a greenhouse to an existing structure. However, the architectural integrated essence of the passive system does not offer much opportunity to be combined with existing facilities. Passive systems require an initial design commitment for solar and energy conservation (Anderson, 1976).

Solar Domestic Hot Water Systems

MPS (1977) exhaustive research of solar domestic hot water systems was conducted because of its retrofit ability. It can be added to any existing structure or combined with either the active or passive systems. This versatile capability of the solar domestic hot water system enables this system to have the greatest solar impact on the energy market. The distribution and auxiliary subsystems are eliminated and the storage subsystem is reduced in size for this system. Also the number of collectors required is less. Therefore, the solar domestic hot water system is very cost effective with an early pay back on investment.

CHAPTER IV

SUMMARY AND RECOMMENDATIONS

The systems, subsystems, and components of solar heating and cooling are complex for a relatively simple technology. The development of conceptual structures is important for a comprehensive understanding of the various solar systems. Equally important is the identification of the cost effective solar subsystems and components.

From the development of the conceptual model for solar heating and cooling systems (Figure 2) the following can be concluded: that solar heating and cooling systems are divided into two main categories - active and passive. These two solar concepts are in turn divided into two types of solar systems - air and liquid.

From the identification of the subsystems and components in Figures 3 and 4, it is determined that most solar systems are composed of the six common subsystems - collector, storage, distribution, transport, auxiliary, and control. The photovoltaic and solar domestic hot water systems are exceptions to this statement. Also the appropriate components are selected that best perform the function of each subsystem. Three additional components adaptable to all the solar heating and cooling systems are indicated in Figure 2. They are the preheat domestic hot water, the heat exchanger, and the heat pump.

The solar system combinations and their degree of importance are recognized for feasible entry on the energy market. The values established by the developed systems will assist curriculum developers, consumers, and builders to understand and promote the use of solar energy.

Recommendations

The implications of this study indicate that solar heating and cooling systems do have a place in the energy market. The training of instructors for solar technology is recommended. It is recommended that this study form the basis for the solar curriculum development necessary for this training and the preparation of designers, technicians, and maintenance personnel.

Additional educational research is recommended as a natural continuation of this study:

1. The preparation of a technical/architectural solar/occupational job task analysis, appropriate program goals, performance objectives, and enabling activities is very appropriate.
2. The development of a survey instrument is suggested to solicit information concerning task frequency as well as the critical tasks.

Also technical and engineering problems which merit further study and research are suggested:

1. A study of the capability and cost effective potential of various hybrid solar heating and cooling systems.
2. A study of the possible solar retrofit combinations that are available for existing structures, including the passive greenhouse system.
3. A study of solar heating and cooling systems recommended for various climates with emphasis on the State of Michigan.
4. A comparison study of the various methods used to calculate the design of the solar subsystems.
5. A research of the advantages of different solar liquid system fluids used in collectors and storage.

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